INVESTIGATION INTO THE SHORT-PERIOD ADVECTIVE CHANGE OF SEA SURFACE TEMPERATURE

W. PATRICK LAW

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Submitted in partial fulfillment of
the requirements for the degree of

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ABSTRACT

An investigation of the advection of sea surface temperature during a 24-hour period is made. Wind-induced currents are shown to be the phenomenon primarily responsible for this short-period advection. The effects of other wind-induced heat exchange processes which reinforce the advective change are estimated. A graphical comparison of isotherm displacements and mean wind field show the apparent response of the sea surface to the changing wind field.

A forecasting model for sea surface temperature change based on the varying wind is developed. This model permits the magnitude of the advective component of sea surface temperature change to be compared to the total local change.

TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	Discussion	
	a. General	2
	b. Ocean Currents	4
	c. Processes Which Reinforce Temperature Advection at the Sea Surface	7
3.	Review of Previous Investigation	9
4.	Data Used	12
5.	Selection of Area for Investigation	15
6.	Investigation	
	a. Graphical	18
	b. Model Development	20
7.	Assessment of Data Accuracy	25
8.	Discussion of Results	27
9.	Summary and Conclusions	32
10.	Bibliography	33
Appendix I	Comparison of Isotherm Displacement and Mean Wind Field for the Gulf Stream Area 7-18 December 1964	37
Appendix II	Summaries of Results of BIMD 6 Statistical Regression Analyses	50

1. Introduction.

This thesis deals with the role of advection in sea surface temperature changes. Attention will be focused on the day-to-day, or short-term effects of advection. Due to the lack of synoptic oceanographic measurements below the surface, this report treats only surface processes.

The most effective mechanisms for sea surface temperature advection will be sought. The magnitude of sea surface temperature advective change and the effects of other wind-induced heat exchange processes which tend to reinforce the advective change will be estimated.

Finally, a forecasting scheme based primarily on wind speed and direction will be developed to predict daily sea surface temperature changes.

2.a. Discussion: General.

The change of the sea surface temperature at a point is made up of two parts: the individual part and the advective part. Much research effort has been expended in trying to relate meteorological parameters to the local daily temperature changes in the upper layers of the ocean. Laevastu, Tabata, Anderson, Masuzawa and others have experimented with various methods of measuring the radiant, latent, and sensible heat exchanges between the oceans and the atmosphere [17], [8], [32], [19]. For the most part the advective change has been ignored, being assumed negligible, or estimated from some sort of mean current and mean gradient.

In many areas, particularly where the sea surface temperature gradient is quite small and currents are weak and variable, this may be a perfectly justified treatment. However, in the Gulf Stream and Kuroshio current areas the horizontal temperature gradients are large, up to 15F per 100 nautical miles. Small cross-isotherm flows for periods of a day or two can make a significant contribution to the interdiurnal sea surface temperature change. For example, a cross-isotherm flow of 0.3 knots and a horizontal temperature gradient of 13F per 100 nautical miles would produce, in 24 hours, a temperature change of approximately one degree. Corton, in his study of physical processes involved in the diurnal cycle of heating and cooling in the upper layers of the ocean, analyzed over 900 bathythermographs taken at half-hourly intervals at Ocean Station Vessel "ECHO", 35N, 48W, between 2 and 21 September, 1959 [37]. After the elimination of known sources of interdiurnal temperature variation and observational errors, the advective heat exchange was cited as the most likely major source of the

remaining variations. The energy exchange involved in advection was estimated to be much greater than that of the vertical exchange processes of heating, cooling and convective mixing.

The question which now arises is, "What measurable atmospheric or oceanographic phenomena are responsible for this day-to-day advective change?" An examination of surface current data found in a marine climatic current atlas reveals the great variability of directions and magnitudes of surface currents, even in areas of supposedly strong permanent currents, such as the Gulf Stream or Kuroshio [35]. Mean currents derived from these charts are unrepresentative of the currents on a given day. Also, the mean currents tend to be parallel to the sea surface isotherms producing a constant and very small advective contribution. Therefore, we must look elsewhere for the phenomena responsible for short-term advective changes.

2.b. Discussion: Ocean Currents.

This paper's concern with ocean currents is with their contribution to the short-period temperature changes in the upper layer of the ocean. Advection of temperature is the means by which a current can contribute to the change.

Consider the processes believed to be responsible for generating and maintaining ocean currents in order to see which can be associated with significant short-period temperature advection. Stommel and others have investigated currents resulting from differential heating of the sea surface [28]. Their results show that for such currents the velocities under actual conditions are insignificant. Goldsbrough calculated the oceanic circulation produced by the uneven distribution of precipitation and evaporation over the sea surface and concluded that evaporation and precipitation generate a system of currents that in general resembles the observed system, but is an order of magnitude too small [12]. It is generally conceded that wind stress provides the energy needed for maintaining the circulation of the upper layers of the ocean. Munk and others obtained mean circulations with many of the observed large-scale features of the ocean from models in which the driving force is the stress exerted by the wind [21].

Now consider the mechanism by which wind influences currents. The effect of the wind on ocean currents is twofold: (1) the stress leads directly to the development of a shallow wind drift and (2) the transport of water by wind drift eventually alters the distribution of density. In response to this new density distribution, there results a current in the same direction as the force responsible for it. This current,

which can be calculated from the density distribution (geostrophic current), is parallel to the isopycnals and, therefore, makes no contribution to density advection. It also tends to be very nearly non-advective for temperature, since the change of density of sea water near the surface is more dependent on temperature than salinity. For example, Fuglister concluded, after the first multiple ship survey of the Gulf Stream area east of Cape Cod, that surface currents flow parallel to the mean isotherms for the upper 200 meters [11]. He found this particularly true where the isotherms were closely packed in the region to the left of the warm core of the Gulf Stream. This conclusion was reached after current vectors determined from GEK observations were superimposed on the isotherm field. In almost all cases it appeared as though the isotherms had been drawn along the current vectors. Over long periods of time, such as a month, the contribution of this flow to the heat budget of this region is huge, even for a scarcely discernible angle between streamlines and isotherms. This fact has been well documented both in theory and from computations based on oceanographic observations. However, for the shorter periods (day-to-day) which are of interest in this report, the contribution of this "steady" flow can be assumed small and fairly constant.

Now consider non-steady current components such as would result from a change in the wind velocity. Ekman is responsible for the classical theory of a pure wind current on a rotating earth. His theory has been the foundation for many investigations into wind-induced currents [7]. One result of such studies is that the direction and magnitude of the wind-induced current is independent of the steady state

current which may already exist in the area. Another is that the wind, in a short period of time, exerts little influence on the density distribution [40]. Post found from data of an oceanographic survey in the eastern North Atlantic that the density distribution (and, therefore, dynamic topography) is relatively unaffected by fluctuations of the local wind [24]. However, the observed surface current was found to depart from the purely geostrophic flow by amounts approximately proportional to observed short-period changes in the wind.

From the above discussion it is reasonable to conclude that the surface current is made up of a steady component related to the density distribution and a fluctuating component induced by the local wind. It has been shown that for short periods the density distribution component is practically non-advective for temperature. Therefore, the short-term wind component must give the primary contribution to the short-term advection of sea surface temperature. This conclusion will be used later in the design of a surface temperature advection model.

2.c. Processes Which Reinforce Temperature Advection at the Sea Surface.

Heat exchange between the atmosphere and the ocean, as well as temperature advection, can be greatly affected by varying winds. The large-scale features of the horizontal distributions of temperature in the lower atmosphere and upper ocean layer tend to be very similar; associated with wind-induced cold advection in the surface waters, there is also cold atmospheric advection. Cold atmospheric advection tends to increase the sea-air temperature difference $(T_s - T_a)$, since the overlying air responds more rapidly to the varying wind than does the ocean. Laevastu, after reviewing previous work done by Bowen, Sverdrup and Shuleikin, gives the sensible heat exchange between the sea and the atmosphere by the formula:

$$Q_h = K_1 + K_2 W (T_s - T_a)$$

where K_1 and K_2 are proportionality constants and W is the wind speed. When $(T_s - T_a)$ is positive, sensible heat is lost by the sea. Therefore, a wind producing negative temperature advection in the sea contributes to higher sensible heat loss from the sea surface [17].

Similarily, latent heat losses should be considered. Examination of a climatic atlas for the North Atlantic Ocean shows that, corresponding to the atmospheric temperature gradient, there is also a wet-bulb temperature gradient. This gradient can be related qualitatively to an atmospheric vapor pressure gradient, with regions of lower vapor pressure corresponding to regions of lower temperature [42]. The latent heat exchange at the sea surface is proportional to the coefficient of latent

heat of evaporation of sea water and the amount of evaporation. Sverdrup gives the evaporation by

$$E = K\,(e_w - e_a)\,W$$

where e_w is the vapor pressure at the sea surface, e_a is the vapor pressure in the air and W is the wind velocity. The advection of cold air is accompanied by the advection of lower atmospheric vapor pressure, resulting in an increased latent heat loss from the sea surface [29]. Even if the overlying air is saturated, evaporation and latent heat loss at the sea surface occurs when $(T_s - T_a) > 0$. In fact, evaporation is greatly facilitated by this condition due to the unstable stratification of the very lowest layers of the atmosphere.

From this discussion it is seen that increased latent and sensible heat losses are associated with cold sea surface temperature advection. Conversely, advective warming at the sea surface is reinforced by decreased latent and sensible heat losses from the sea surface.

3. Past Investigation.

The long-term effect of wind-induced advection on sea surface temperature has been investigated by Namias and by Eber [22], [6]. It was found that wind-induced advection is one of the mechanisms through which conditions in the surface layer of the ocean can be affected by atmospheric fluctuations. Eber determined anomalous sea temperature advection using surface water displacements computed solely from monthly mean geostrophic wind anomalies. Observed sea surface temperature anomalies during the two seasons considered were then compared with the computed advective sea temperature anomalies. Good agreement was found for the winter period and poor agreement for the fall period. The results for the winter period showed a stronger correlation between computed advection and observed sea temperature anomalies than was found earlier by Namias for the same two cases. Eber's principle modification to Namias's procedure was that he attempted to take into account the initial state of the ocean. It was concluded that advection had the dominant effect on sea surface temperature in the winter case, but was subordinate to other, unspecified processes during the fall.

Bjerknes showed that the net heat loss of the ocean to the atmosphere was significantly dependent on the average strength of the wind and, therefore, experienced large variations between years of "low index" and "high index" atmospheric circulation [1]. In a classic example of air-sea interaction he showed that changes in intensity of oceanic circulation are mainly dictated by changes in atmospheric circulation and that resulting changes in the temperature field of the ocean surface

in turn influence the thermodynamics of the atmosphere.

Chase worked on variations of a much shorter time period with data from Frying Pan Shoals lightship off the Carolina Coast in the fall of 1956 [4]. He found that warming of the surface water usually occurred ahead of cold fronts (when southwesterly winds were prevalent) and cooling was experienced after the frontal passage (when northerly winds prevail). He acknowledged that the transfer of heat to the atmosphere might have been responsible for the lowering of the water temperature in the wake of cold fronts. However, corresponding drops in the salinity of the water column made such an explanation inadequate. The pronounced salinity gradient known to exist in the area due to runoff north of the lightship strongly indicates that the observed changes were advective.

Hanzawa reported on remarkable and very abrupt alteration of water masses at Ocean Station Vessel "EXTRA", located at 39N and 153E [13]. He investigated three instances of apparent lateral fluctuation of the oceanic polar front separating the Kuroshio and Oyashio currents. By use of time cross-sections of temperature and temperature-clorinity diagrams, characteristic properties of water before and after the penetration of warm or cold water were examined in detail. He was able to conclude that the wind plays an important role in the advection of cold or warm water. As would be expected, the sign of the advective change differed according to whether the dominant cyclone in the area passed to the north or to the south of the station.

In 1960, Laevastu estimated directly the wind-induced advection on a synoptic scale. However, in his heat budget calculation, he integrated

its effect over periods of from 10 to 15 days [17].

These examples show quite clearly that the effect of advection by wind-induced currents can, in many areas, be significant in both long and short-term sea surface temperature variations.

4. Data Used.

In order to estimate the short-term wind-induced temperature advection, one needs at least: (1) day-to-day sea surface temperatures, (2) horizontal temperature gradients, and (3) winds. The U. S. Fleet Numerical Weather Facility (FNWF) provided computer-prepared sea surface temperature (SST) hemispheric analyses twice daily on a scale four times larger than the analyses prepared for routine fleet distribution. These are used to estimate the short-term advective changes because they are the only hemispheric scale, daily, synoptic SST analyses prepared on a routine basis. The computer method of analysis is well described by Wolff [34]. An example of the SST print-out is shown in Figure 1. These analyses provide the temperature gradients and the temperatures (at grid points spaced approximately 100 nautical miles apart) from which day-to-day local changes are estimated. Geostrophic winds are determined from FNWF surface pressure analyses prepared four times daily. Since an aim of this study is to contribute to the advective portion of an eventual SST forecasting scheme, it is convenient to use the prognostic geostrophic wind for estimating the wind-induced advection, since it is readily available. Also, the geostrophic wind is often more representative of the wind field affecting an area than is an isolated wind observation.

Additional data used here are published by the Japanese Meteorological Agency from observations taken during 1950 at ocean station "XRAY", located at 39°N and 153°E. These data included standard meteorological observations and sea surface temperatures reported eight times daily.

EXAMPLE OF A SST PRINT-OUT WITH APPROPRIATE LATITUDE, LONGITUDE AND GEOGRAPHICAL REFERENCES ADDED

Figure 1

There are, additionally, hydrographic data extending to depths greater than 1000 meters once a day. Unfortunately, no synoptic SST analyses were available for this region and, therefore, no synoptic horizontal temperature gradients. Instead, gradients were estimated from monthly mean sea surface temperature charts for the northwestern Pacific prepared by the Japanese Meteorological Agency from data for the ten-year period of 1950 to 1959 [20].

5. Selection of Area for Investigation.

An important step in this investigation was the selection of an area in which the advective contribution is clearly seen. The SST and pressure analyses of FNWF cover the entire northern hemisphere, allowing a choice of areas for possible consideration. To maximize the advective temperature change, the area should have strong horizontal SST gradients. To minimize the influence of errors in SST analyses, the area should have a high density of ship reports. Since this paper does not consider the short-period variability of the radiative heat exchange across the sea surface, the area should have a relatively small and constant radiative heat exchange. Radiative heat exchange between the ocean and the atmosphere varies significantly with the time of the year. In the northern hemisphere it is large and positive for the oceans in late June, with small values, either positive or negative, in late December. Great variability in the day-to-day radiative exchange can be attributed to varying cloudiness. A large and fairly constant cloud cover minimizes the variability due to radiative heat exchange.

With these considerations in mind, it was decided to examine the Gulf Stream area east of Cape Cod and south of Newfoundland. This area has the strongest horizontal sea surface temperature gradient observed anywhere. As for the density of ship reports, this is the largest area having a relatively high density of ship reports in the northern hemisphere. Figure 2 shows the average number of reports for December, 1964, close enough to a grid point to be considered in the FNWF analysis of SST.

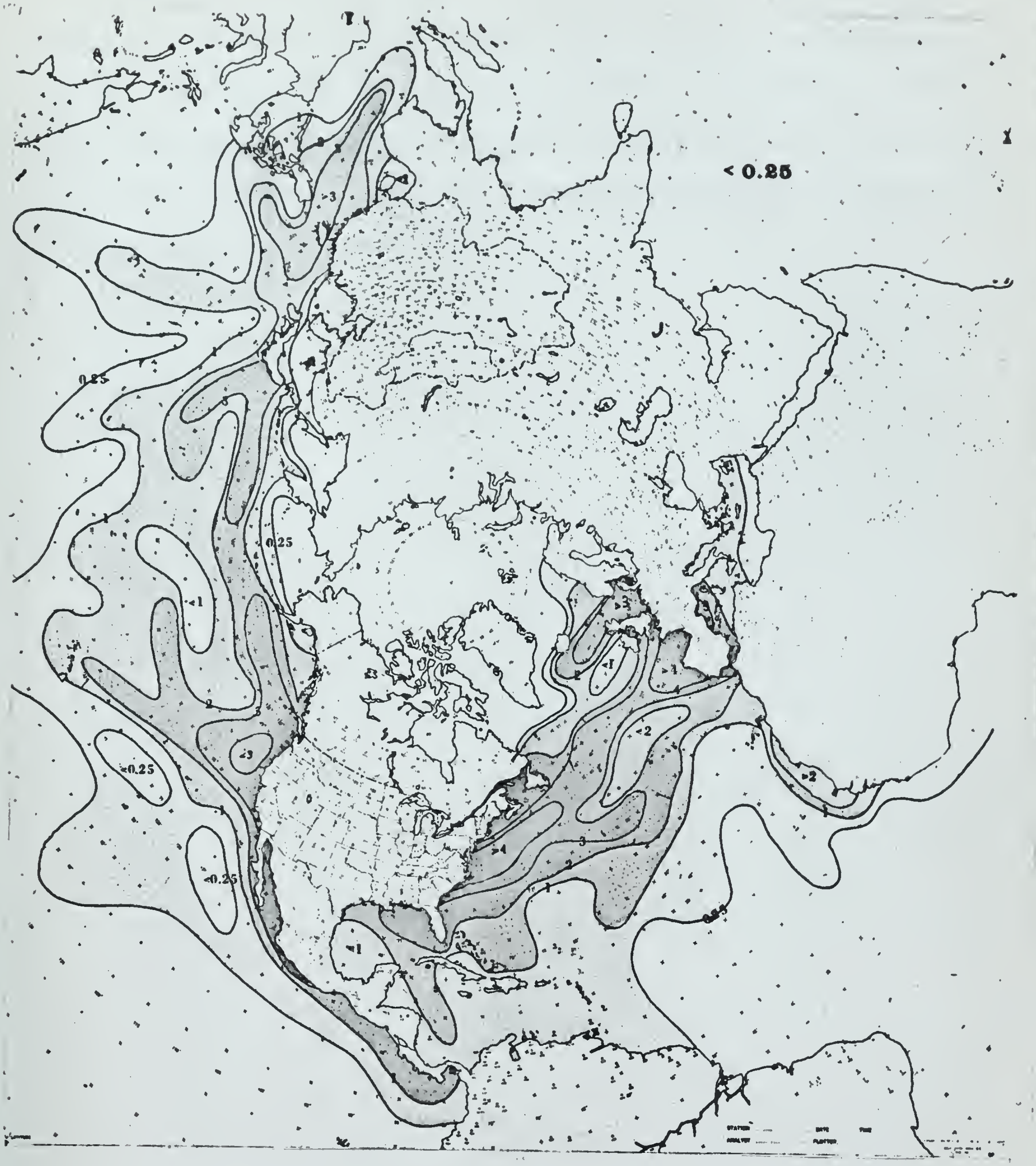

Figure 2

Density of Sea Surface Temperature Reports for December 1964 (After FNWF).

Concerning radiative exchange, the climatic atlas for the North Atlantic Ocean shows that cloudiness is high in this area in December [42]. In fact, some 50% of the time the skies are overcast. Therefore, the radiant exchange is expected to have small absolute variability. The effect of diurnal temperature variation is eliminated by considering periods of not less than 24 hours.

6.a. Investigation: Graphical.

For a broad look at this wind-induced advective phenomenon, graphical overlays are used to show the 24-hour displacement of the isotherms from 0000Z over the entire area. Then, this displacement field is overlain by a time-mean surface-pressure field formed by graphical addition of the four six-hourly surface-pressure charts beginning at 0000Z. A subjective relation between areas of warming and cooling at the sea surface and the wind field becomes apparent.

The preparation of these time-mean charts introduced a lag of approximately three hours between the wind and the isotherm displacement fields. The 1800Z chart was the last of the four used to determine the mean pressure field; therefore, the geostrophic wind, W_g, determined from it more nearly represents the average wind for the period of 2100Z of one day to 2100Z of the next. Bowden found from GEK measurements that, even during a radical wind shift, when wind velocities ranged from 18 to 30 knots, the current direction changed and approached a steady value within three hours [2]. Thus, the lag of the advective calculations behind the wind field corresponds approximately to the time required for the production of steady state currents.

In Appendix I are charts on which the 24-hour isotherm movements and corresponding mean surface-pressure patterns are shown. Accompanying each diagram is a discussion of the wind and SST fields and the apparent response of the isotherm field to the wind. A significant warming or cooling trend for an area is indicated when two or more

adjacent isotherms are displaced in the same sense. Also, the displacement should encompass a distance along the isotherms of approximately 150 miles, indicating that it is the result of changes at two or more grid points.

6.b. Investigation: Model Development.

A model now will be developed which attempts to describe the local SST change based on the varying wind. The equation for the time rate of change of temperature for an element of fluid moving at velocity $\mathbb{V}$ may be stated as

$$dT/dt = \partial T/\partial t + \mathbb{V} \cdot \nabla T \tag{1}$$

where T is the sea surface temperature, t is time, and $\mathbb{V}$ is current velocity. Transposing gives

$$\partial T/\partial t = dT/dt - \mathbb{V} \cdot \nabla T \tag{1a}$$

or

$$\partial T/\partial t = (\partial T/\partial t)_1 + (\partial T/\partial t)_2 \tag{1b}$$

where

$$-\mathbb{V} \cdot \nabla T = (\partial T/\partial t)_1$$

is the advective part of the local temperature change; and

$$dT/dt = (\partial T/\partial t)_2$$

is the individual part.

It is now proposed to relate the observed local change to values estimated for advective and individual parts. The discussion which follows will explain the methods used to evaluate the contribution made by each of these to the total local change.

To evaluate $(\partial T/\partial t)_1$, only the cross-isotherm component of velocity needs to be considered, since it alone contributes to advective change. Based on the discussion in section 2.b., it will be assumed that the wind-induced current is responsible for all of the cross-isotherm flow of the surface current.

The first step is to find a relation between the wind and current. Numerous investigators have attempted to determine the "wind factor", V/W, the ratio of the wind-induced current to the wind. Their results vary, so a choice must be made. Thorade, as reported by Defant, found the empirical relation often quoted,

$$V = \frac{0.0127W}{\sqrt{\sin \phi}}$$

where V is the speed of the wind-induced current, W is the surface wind observed at some standard height above the sea surface, and ϕ is the latitude [5]. For the area of the Gulf Stream covered in this investigation, the mean latitude, ϕ, is 43°; and V/W= 0.015, if Thorade's expression is appropriate for the advecting current.

Hughes attempted to determine the drift due to the wind-induced current by measuring the drift of plastic envelopes [15]. He compared the actual drift to averaged gradient winds, W_{gr}, determined from surface atmospheric pressure analyses and found $V/W_{gr} = 0.022$, with the surface wind over the open ocean assumed to be $(2/3)W_{gr}$, V/W = 0.033. This is approximately twice the value found using Thorade's relation. Hughes also concluded that the drift of the envelopes was along the isobars. Hughes' value can be considered valid for only a very thin

surface layer and is not completely applicable to this investigation since the FNWF SST analyses use many observations from ship's injection thermometers located some distance below the surface.

In the present study the wind-induced surface current will be assumed parallel to W_g, with surface windspeed 2/3 W_g. The wind-induced current will be assumed to be given by V/W = 0.02, nearer Thorade's value. When observed winds are used, the current directions will be assumed 22.5^{o} to the right of the observed surface wind.

To find the relation between the individual and advective parts of the local change, recall the similarity of the horizontal temperature structures of the sea surface and lower atmosphere discussed in section 2.c. It was noted that the wind advecting low sea temperature was also associated with cold atmospheric advection, leading to increased sensible and latent heat losses at the sea surface. Conversely warm sea surface temperature advection was shown to be accompanied by less sensible and latent heat loss at the sea surface. If the non-advective component of change is proportional to the winds, we can write

$$(\partial T/\partial t)_2 = C + K(\partial T/\partial t)_1 \tag{2}$$

where C is that part of the individual change which would occur in the absence of atmospheric advection, including radiant exchange, and K is a measure of the anamalous vertical heat flux, or that part of the latent and sensible heat exchange which varies with the wind.

Substituting from equation (2) into (1b), we obtain

$$\partial T/\partial t = C + (1+K)(\partial T/\partial t)_1 \tag{3}$$

or

$$\partial T/\partial t = C - (1+K)(\mathbb{V} \cdot \nabla T) \tag{3a}$$

and $\mathbb{V} \cdot \nabla T$ can be determined from the available charts.

Now, the induced current is

$$\mathbb{V} = 0.02\,(2/3)\,\mathbb{W}_g$$

so equation (3a) becomes

$$\partial T/\partial t = C - (1+K)(0.02)\,2/3\,\mathbb{W}_g \cdot \nabla T \tag{3b}$$

Using the FNWF analyses in the Gulf Stream area for the period 7 through 18 December 1964, the observed local change, $\partial T/\partial t$, was determined at selected grid points, located as shown in Figure 1. The time-mean geostrophic wind described in section 6a, together with the horizontal temperature gradient taken from the FNWF SST analyses, was used to determine the advective quality, $(0.013)\ \mathbb{W}_g \cdot \nabla T\ (24)$[1]. A scatter diagram of the observed local change plotted against the advective quantity was prepared. Using the data from OSV "XRAY",

[1] This 24 converts W_g, which is measured in nautical miles per hour, to nautical miles per day. The advective quantity and the total local change are, therefore, both expressed in $^oF/24$ hours.

as discussed in section 4, for the period 7 August to 11 September, a similar scatter diagram was prepared. The statistical regression program, BIMD6, was used to fit regression curves to these two sets of points, one in the Gulf Stream area and one in the Kuroshio [39]. Appendix II contains the plotted scatter diagrams with the fitted regression curves. Also included in Appendix II are summaries of the BIMD6 statistical regression analyses computed for these two investigations.

From the fitted regression curves the constants C and K are determined for each investigation. Thus, it is possible to determine the size of the advective component relative to the local change and to the individual component of sea surface temperature change in each location studied.

7. Assessment of Data Accuracy.

It is beyond the scope of this paper to discuss quantitatively the effect of inaccuracies in the data on the sea surface analyses, but a qualitative assessment is undertaken. The analyses prepared by FNWF are the most objective sea-surface temperature analyses presently available. Errors associated with observing, reporting and analyzing the sea surface temperatures are mutually independent. In areas where there is a high density of ship reports the noise due to these errors tends to be reduced by the averaging procedures of the analysis. A value taken from the analysis is, therefore, more representative of temperature features of the scale (greater than one mesh length) treated in this report than is any single reported observation. Unless specifically excepted, the wind and the sea-surface temperature information from the FNWF analyses will be assumed to portray accurately the existing conditions in the detail permitted by the grid-spacing.

To determine the representativeness of the mean gradients used at OSV "XRAY", the isotherm patterns shown in this area by FNWF synoptic analyses during a similar period were examined. Waves of great amplitude were not shown on the isotherm patterns. There was a day-to-day shift of the isotherm positions, but by and large the gradient remained fairly constant in magnitude and direction. The use of these mean gradients in the calculation of the advective term, therefore, appears likely to give results comparable to those using FNWF data in the Atlantic.

In both areas intense temperature features of short wavelength, such as those shown by Fuglister and others in multiple ship surveys

of the Gulf Stream Area, may significantly contribute to the advective change at a grid-point, but are not included properly in the advective calculation because of their small wavelength and the smoothing procedures used in the analyses [10], [11]. The omission of such features may make an important contribution to errors in the calculated advection.

8. Results.

As noted earlier, the sea surface isotherm displacements shown in Appendix I appear to be in response to the day-to-day changing wind field; but the displacements are too large to be accounted for solely by wind-induced sea-surface temperature advection. The agreement between the wind and the isotherm displacements is best when the wind fields are strong and steady.

During periods of light and variable winds there appears to be little relation between the isotherm displacements and the wind field. During these periods, areas of warming or cooling, which had occurred in response to the most recent period of strong winds, appear to move from west to east parallel to the isotherms. The speed of movement is much greater than the permanent current which is known to exist in the area and slower than the movement of the wind field. An example is the warming area which occurred in response to southerly winds over the western third of the area on 12 December. The next day was a period of very light winds during which this area of warming appeared to move east at about 15 knots and decreased in size. On 14 December, the winds continued light and this area again diminished in size and moved eastward. It seems likely that, during periods of light winds, the warming patterns induced by strong winds of the previous period tend to persist but decrease due to the dying out of the transient wind currents. Another possible contributor to persistence of warming trends with lighter winds is the analysis method employed by FNWF. It uses an 84-hour data collection period placing emphasis on the latest reports

to make the analysis more nearly refer to a single time. This rather lengthy collection period tends to produce a lag in the response of the analysis to actual condition. A lag was not particularly noticeable at any other time during this investigation; and, in fact, the analysis appeared to respond quite well to the changing wind field.

Consider now the regression curve determined for the Gulf Stream area investigation:

$$\partial T/\partial t = 0.017 + 1.445 \; \mathbb{V} \cdot \nabla T.$$

Comparing with equation (2) in section 6.b gives (K + 1) = 1.445, K = 0.445 and C = 0.017. This implies that the advective term is about twice the value of the anomalous vertical heat flux, and accounts for approximately 2/3 of the total observed change. The standard error of estimate for this regression line is 0.97 which is large compared to the standard deviation of 1.2 for the local temperature change.

The size of the advective term may be overestimated, since the sea surface temperature changes taken from the computer analyses don't entirely reflect the variability of the sea surface temperature. The fact that the analysis uses a linear fitting method and a smoothing filter tends to reduce the magnitude of the local change at a grid point. This smoothing of the data by the analysis also reduces the horizontal temperature gradients. If the scale of the temperature gradients is small compared with a grid-distance, then the FNWF analysis underestimates the gradients. This, in turn, leads to underestimates in calculations of the advective quantity $\mathbb{V} \cdot \nabla T$. All calculations

show the advective quantity to be smaller than the total change. The constant K in equation (3b) may be thought of as including some correction for this effect. But, if advection is accurately estimated, the advective change can be considered twice the anomolous vertical heat flux for this area and period of time.

Examine the value for the constant C determined in this investigation. For the winter situation $C \doteq 0$ seems reasonable. The radiative transfer would be expected to be small but positive at this time of year, since back radiation should be slightly less than a small incoming solar radiation. However, one would expect the non-wind-induced latent and sensible heat contribution to be negative; and, therefore, C should be equal to or less than zero.

At OSV "XRAY" the computed regression curve gives

$$\partial T/\partial t = 0.01 + 1.99 \ \mathbf{V} \cdot \nabla T.$$

In this case $(K + 1) = 1.99$, $K = 0.99$ and $C = 0.01$; $K \doteq 1$ implies that the advective term is approximately equal to the anomolous part of the vertical heat flux and accounts for half of the total local change. This is probably a more representative estimate of the relative size of these two quantities. A value of $C \doteq 0$ seems less reasonable in this case than for the winter. The radiant exchange across the air-sea interface in this, the late summer, should be a moderately large positive contribution to the ocean's heat budget; and one would, therefore, expect C to be much greater than it was during the winter. The standard error of estimate associated with this regression line

was 0.64 which is quite large compared to the standard deviation of 0.71 for the local temperature change.

Best fit regression curves through fourth order were computed for both sets of data. Although the size of the residuals decreased slightly with increasing order of the regression curves, only the first order coefficient was found to be statistically significant.

The model used in these investigations does not consider the day-to-day variability of the radiant exchange or vertical mixing. In the summer, when the amount of cloudiness is small and relatively constant, the variability in the day-to-day radiant exchange is small. However, since this is the time of the year when the radiant exchange can be a large positive gain for the ocean, a small change in cloudiness may be responsible for a large change in the radiant energy available at the sea surface.

The model also ignores the influence of vertical mixing. Due to a strong negative temperature gradient just below the surface at OSV "XRAY" during this period, wind mixing could contribute cooling at the surface even when warm advection takes place due to a strong southerly wind. These two factors could account for the low correlation coefficient of 0.2 found in the summer case between the advective and the total change.

A possible improvement in the results of this model would be realized if C were made a function of the forecast incoming solar radiation. A formula similar to that advanced by Laevastu could be used, in which the incoming solar radiation, Q_s is expressed

$$Q_s = SAD\,(1 - 0.0006\,c^3),$$

where S is a proportionality constant varying seasonally and with location, A is the noon altitude of the sun, D is the length of day from sunrise to sunset in minutes and c is the cloudiness expressed as a whole number of tenths [16] .

A graphical evaluation of the sea surface temperature and wind fields, similar to that shown in Appendix I, was undertaken in the same Gulf Stream area during a spring and early summer season. The response of the sea surface temperature to the expected advection (wind field) was not as good as for the winter investigation. Explanations for this might be wind-induced mixing and a greater variability in the day-to-day cloudiness and its effect on the radiant exchange. It should be recalled that Eber and Namias both found substantially less agreement between the computed advective anomaly and observed temperature patterns in the fall than in the winter [6] , [21] .

The fall and spring are periods of rapidly changing meteorological conditions, all of which may have effects on the sea surface temperature. It appears possible that the variability of many other factors may mask the effects of wind-induced advection during these transitional seasons.

9. Summary and Conclusions.

This paper has investigated the short-period response of the sea surface temperature to the changing wind field. This response is in two forms: (1) direct advection of sea surface temperature by wind-induced currents and (2) indirectly by atmospheric advection which changes the sea-air temperature differences, thereby affecting the sensible and latent transfer at the sea surface.

In areas where strong horizontal temperature gradients exist, the advection of sea surface temperature was estimated to account for approximately one-half of the total local sea surface temperature change.

The surface current component directly induced by the wind stress was advanced as the phenomenon responsible for the short-term advection of temperature at the sea surface.

Wind-induced advection is more noticeable in the winter and summer seasons than during the transitional seasons of spring and fall.

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APPENDIX I

Comparison of isotherm displacement and mean wind fields for period 7-18 December 1964.

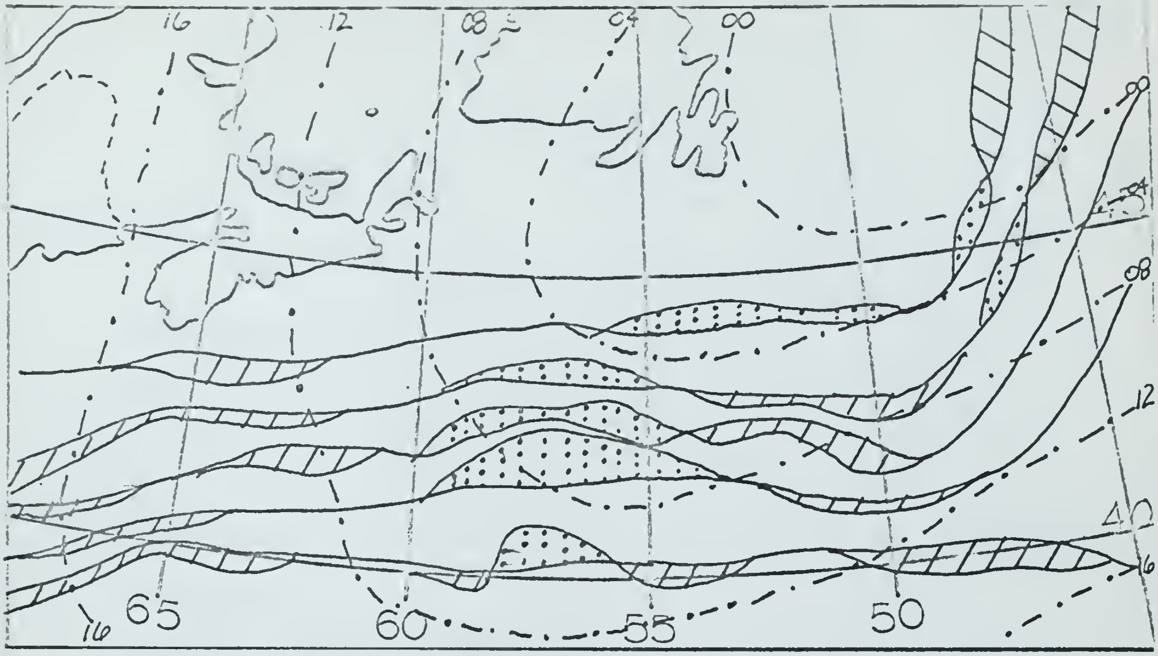
Legend:

Isobars expressed in ten and units of millibars.

Isotherm not labelled. On each chart the 45, 50, 55, 60 and 65F isotherms are shown except for the period 17-18 December when the 4, 8, and 12C isotherms are shown.

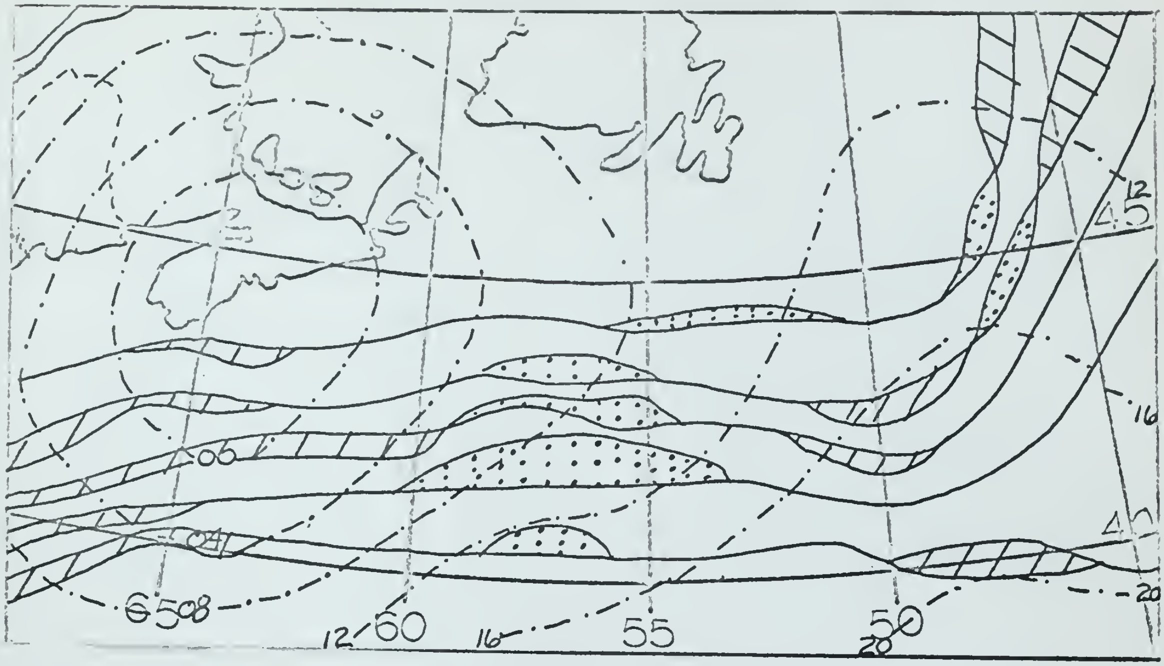
Indicates area of sea surface cooling.

Indicates area of sea surface warming.



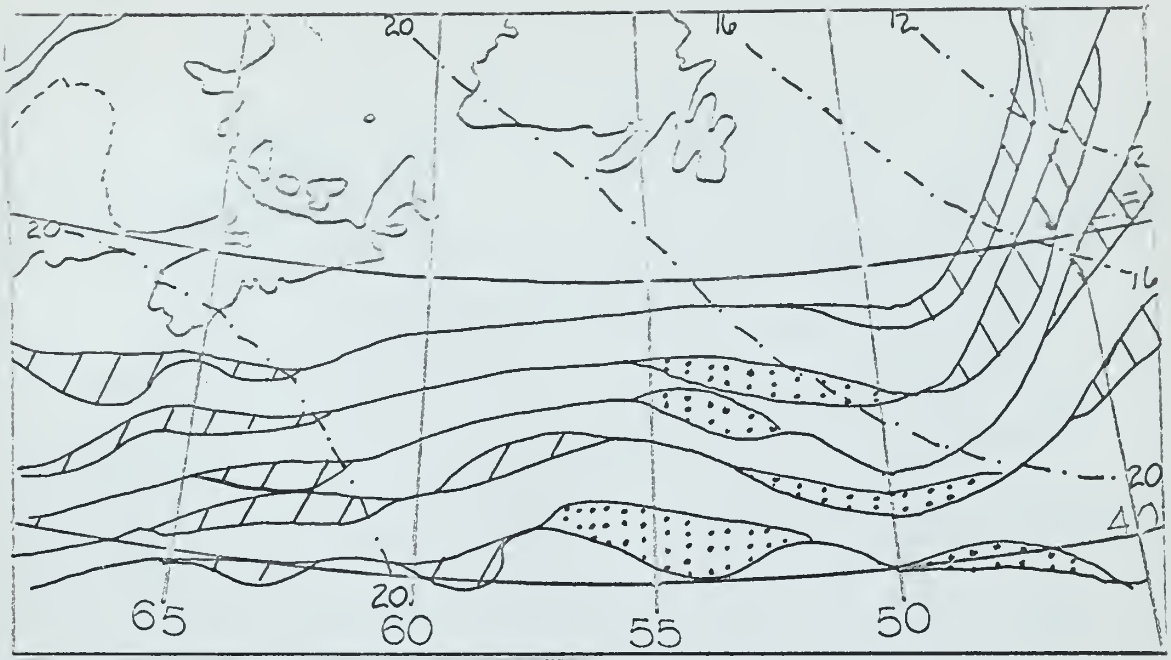
7-8 December

The sea surface showed cooling throughout the area except for the warming evidenced in the center. In general, there is little agreement between areas of cooling and northerly winds or warming and southerly winds.



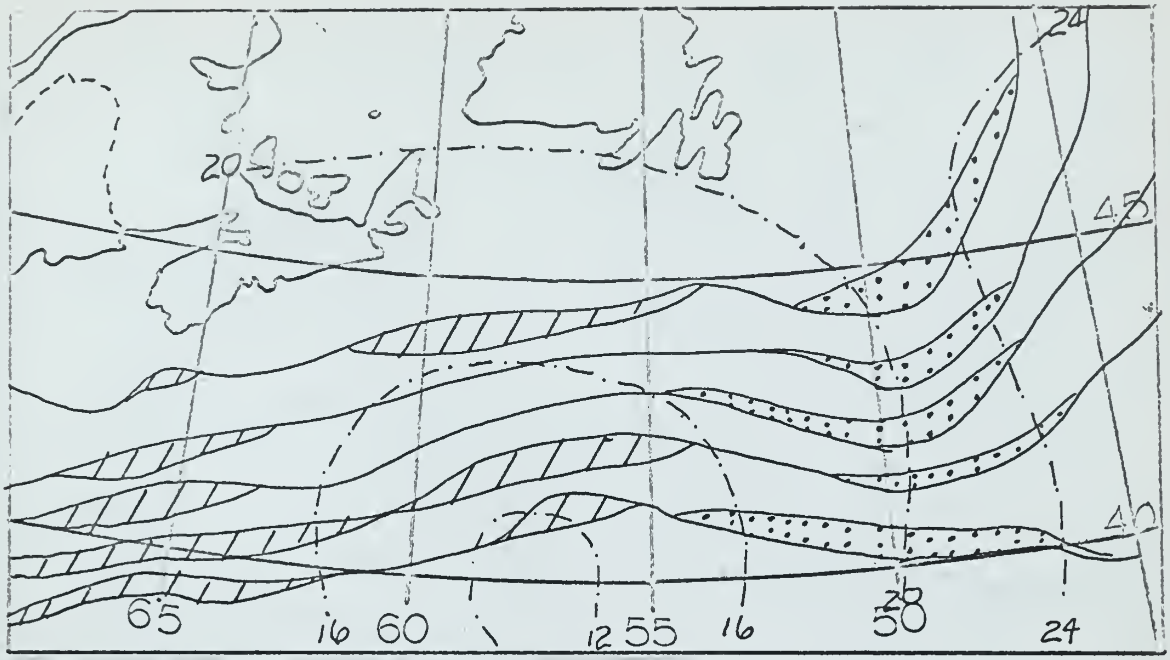
7-8 December

Shown above are the isotherm displacements for the period 7 to 8 December and the 0000Z, 7 December surface pressure analysis. A cyclone which had been nearly stationary just to the east until 0000Z on the seventh, deepened and moved across the area at about 50 knots. The movement was so rapid that the sea surface apparently did not have time to respond to the changing wind field. This wind field is considered representative of that which prevailed before the cyclone began its rapid movement; as can be seen the southerly winds correspond to the area of warming.



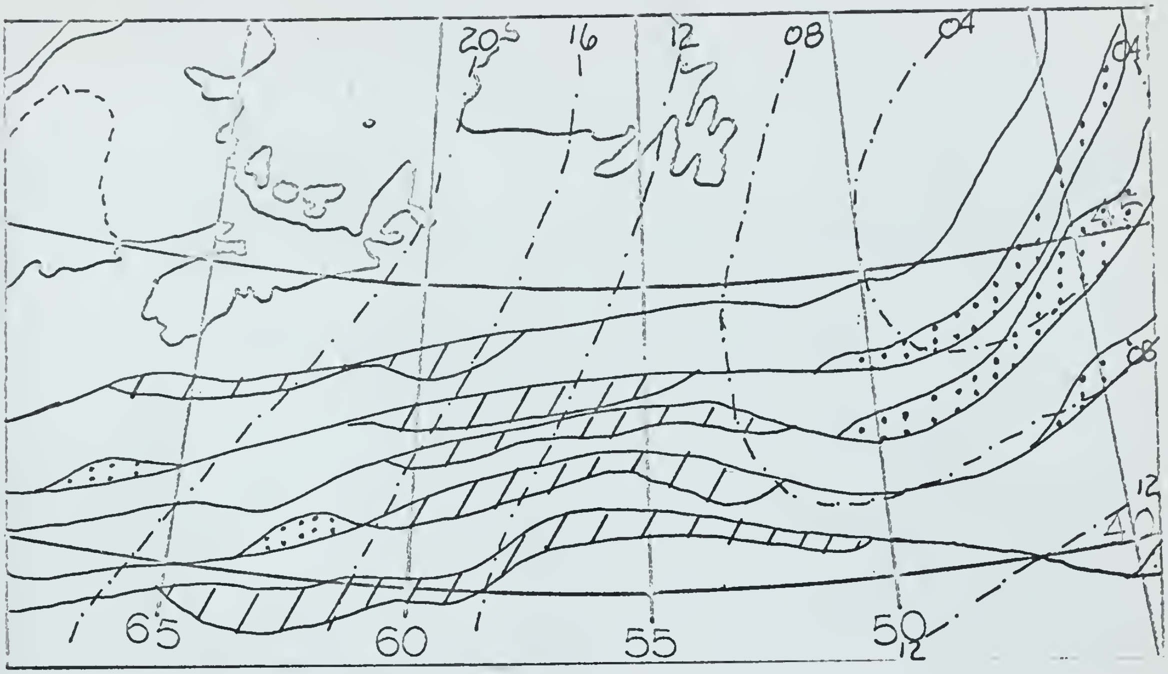
8-9 December

The cooling in the eastern one-third of the area agrees with the strong northwesterly wind which existed there. The area of warming in the center may be a residual from the well developed warming area which was located to the west on the previous day. This area of warming is approximately the same size as on the previous day and has been displaced along the isotherm about 350 miles to the east.



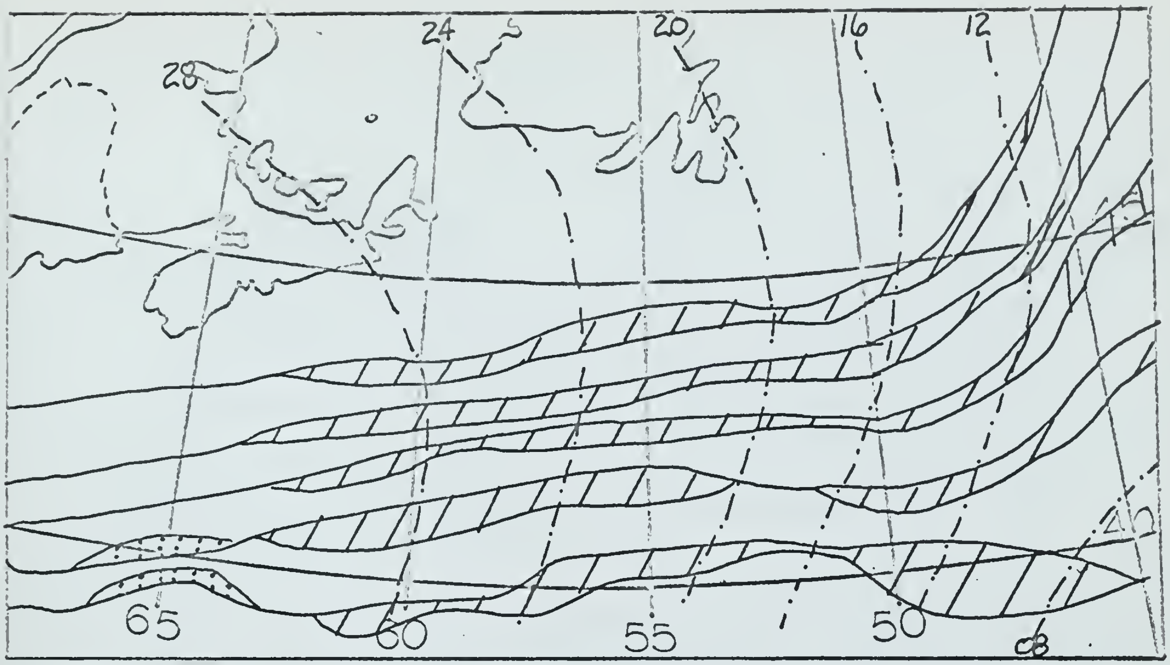
9-10 December

The sea surface temperature shows cooling over the western two-thirds of the area. This was also an area of northerly winds. The warming in the eastern one-third of the area coincides with the area of southerly flow.



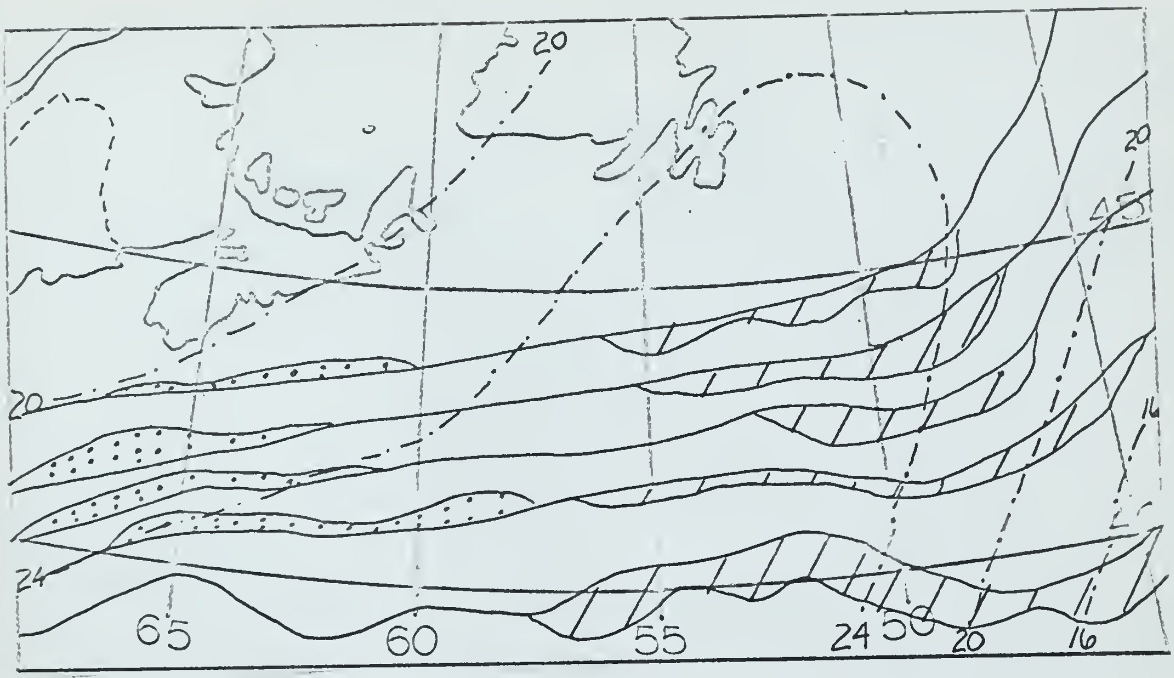
10-11 December

The western three-fourths of the area was dominated by northerly winds and the eastern edge of the area has been under the influence of southerly flow. The sea surface shows a general area of cooling where the northerly winds persisted and warming where there were southerly winds. It is interesting to note that, as the northerly winds became predominant over more of the area, the sea surface cooling also covered more of the area.



11-12 December

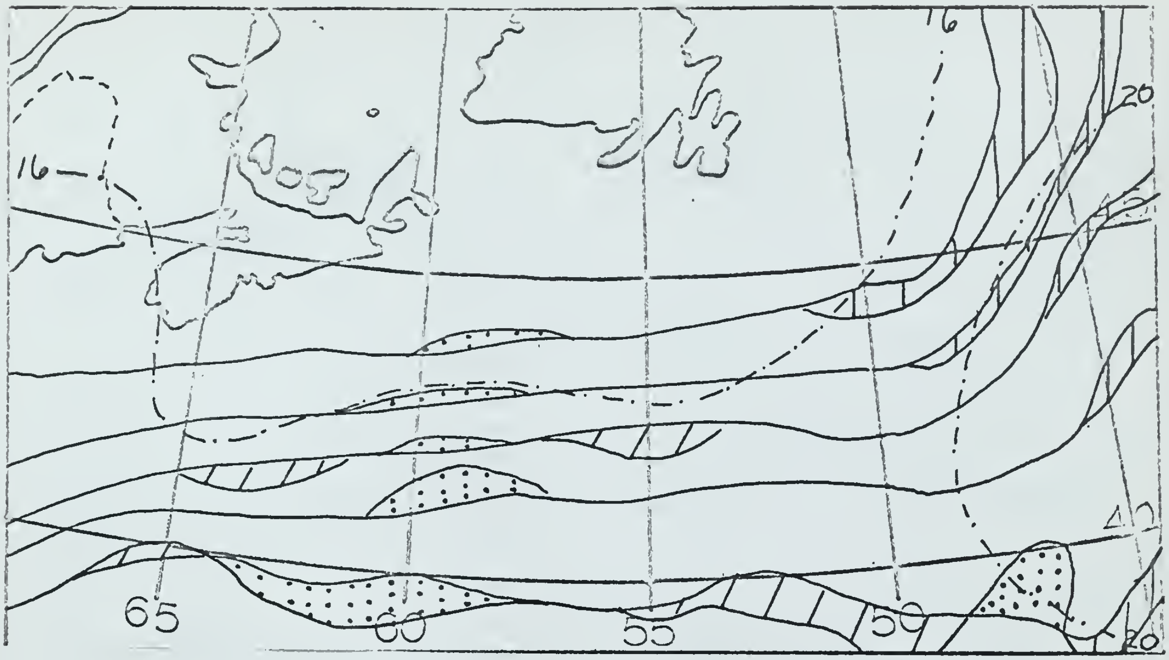
During this period northerly winds moved into and now dominate the flow over the entire area. These winds are reflected in the sea surface temperature which showed cooling over all of the area.



12-13 December

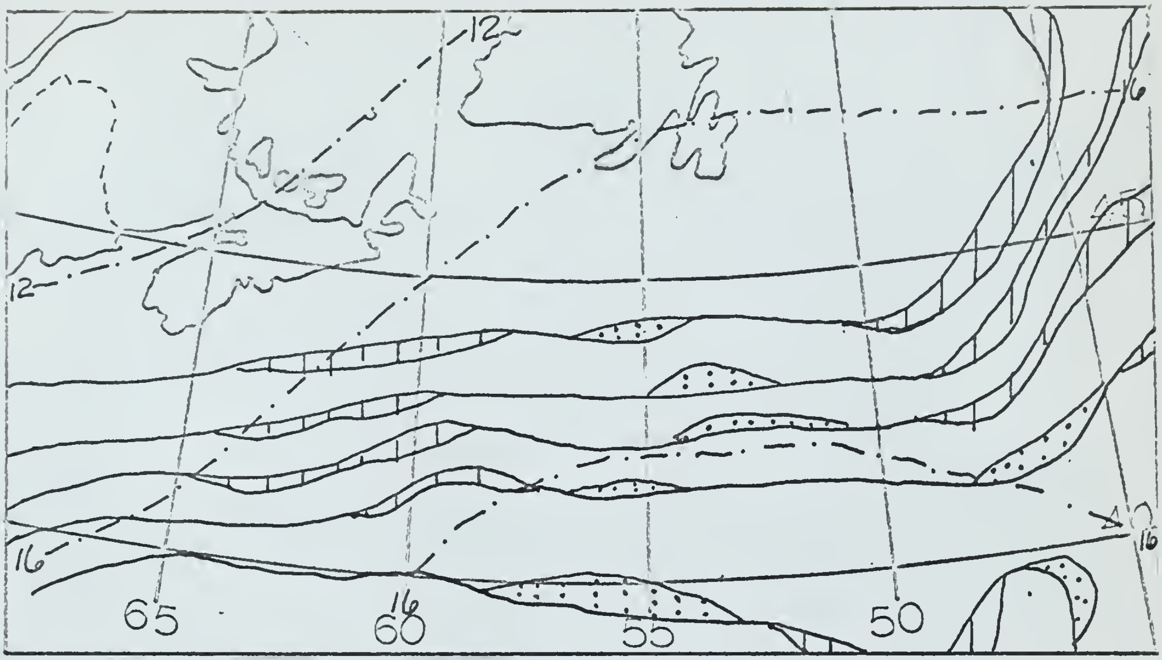
Northerly winds were experienced over the eastern one-third of the area and southerly winds over the western one-third. The areas of sea surface cooling and warming appear to agree with the areas of northerly and southerly flow respectively. That the cooling persists into the ridge area may be due to the fact that a lag exists between the changing wind field and the sea surface response to it.

During the period for 10 to 13 December, the area of northerly winds and cooling sea surface have moved across the area together.



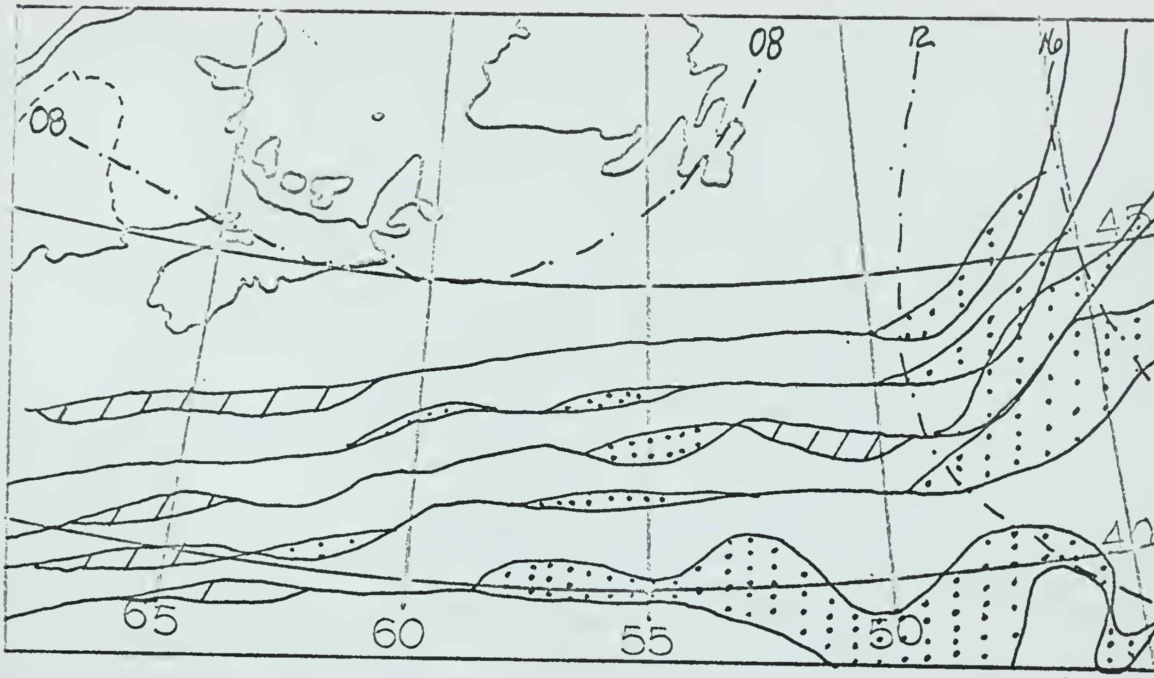
13-14 December

No particularly strong winds existed in the area. Note that the pronounced warming in the western third of the area during the previous period has moved east and diminished in size. The same has happened to the cooling area which was noticed in the eastern third of the area on the previous chart.



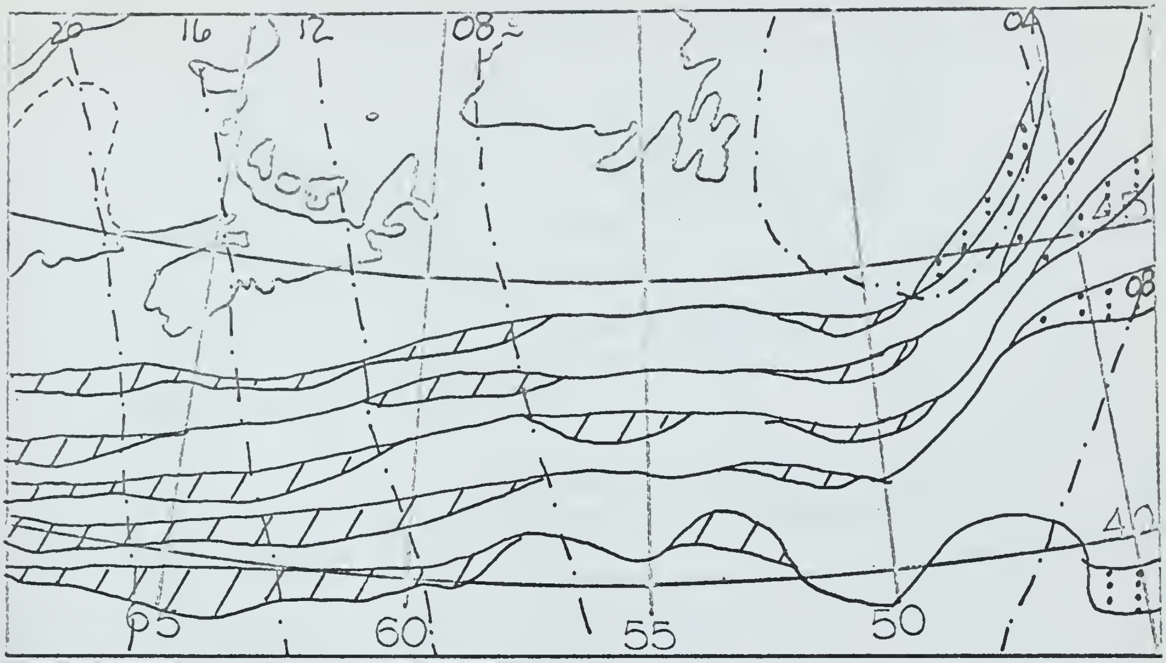
14-15 December

Weak and variable winds existed over the area. The sea surface warming area first noticed on 12 December has apparently continued to move east and diminished in size. The cooling at the edge of the area has persisted from the previous period.



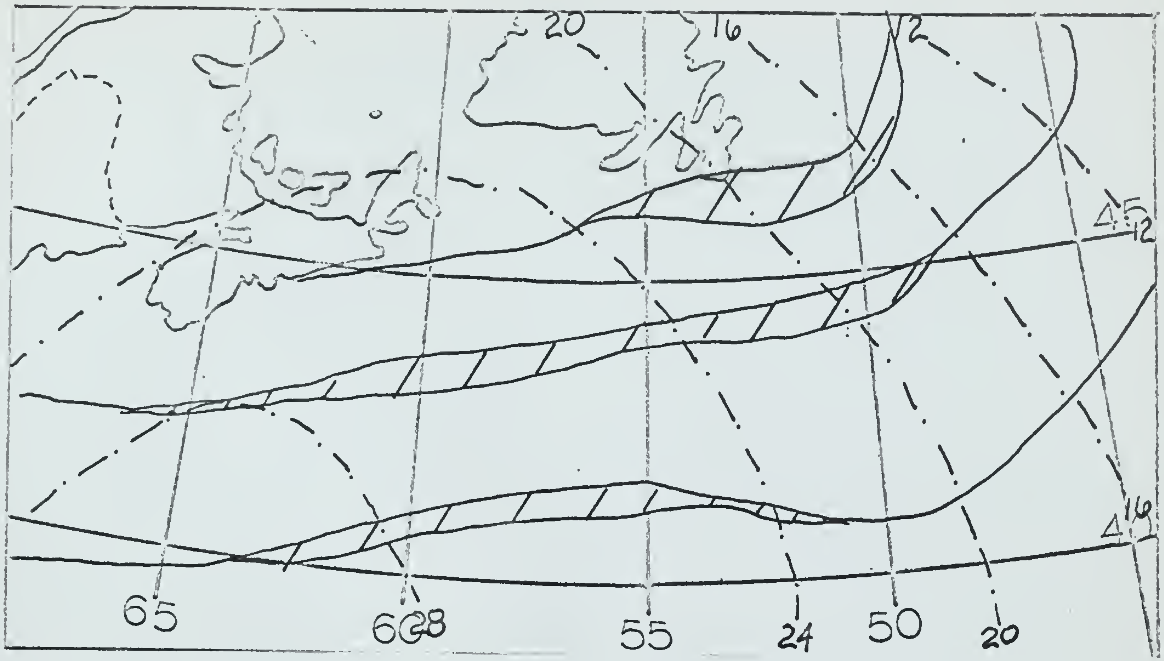
15-16 December

The eastern half of the area has come under the influence of southerly winds, while the western half has continued to show light winds. The sea surface warming in the eastern half of the area is apparently in response to this southerly flow.



16-17 December

Strong northerly flow has moved into the western three-fourths of the area. This is the same area where sea surface cooling has occurred. The eastern edge of the area shows warming, possibly in response to the southerly winds in that area.



17-18 December

As the northerly winds have moved into and covered the area, the cooling at the sea surface has apparently followed and now dominates the area.

APPENDIX II

Summaries of results of BIMD 6 Statistical Regression Analyses.

GULF STREAM
WINTER 1964

Variable no.1 is $V \cdot \nabla T$
Variable no.2 is ΔT_{24}

```
PROBLEM NO.     1- 0
NO DATA TRANSFORMATION
SAMPLE SIZE    49
NO. OF VARIABLES  2       NO. OF VARIABLES DELETED  0
DEPENDENT VARIABLE IS NOW NO.  2
COEFFICIENT OF DETERMINATION    .4024
MULTIPLE CORR. COEFFICIENT      .6344
SUM OF SQUARES ATTRIBUTABLE TO REGRESSION          30.27327
SUM OF SQUARES OF DEVIATION FROM REGRESSION        44.95162
VARIANCE OF ESTIMATE            .95642
STD. ERROR OF ESTIMATE          .97797
INTERCEPT (A VALUE)             .01663
STD. ERROR OF INTERCEPT         .14152
```

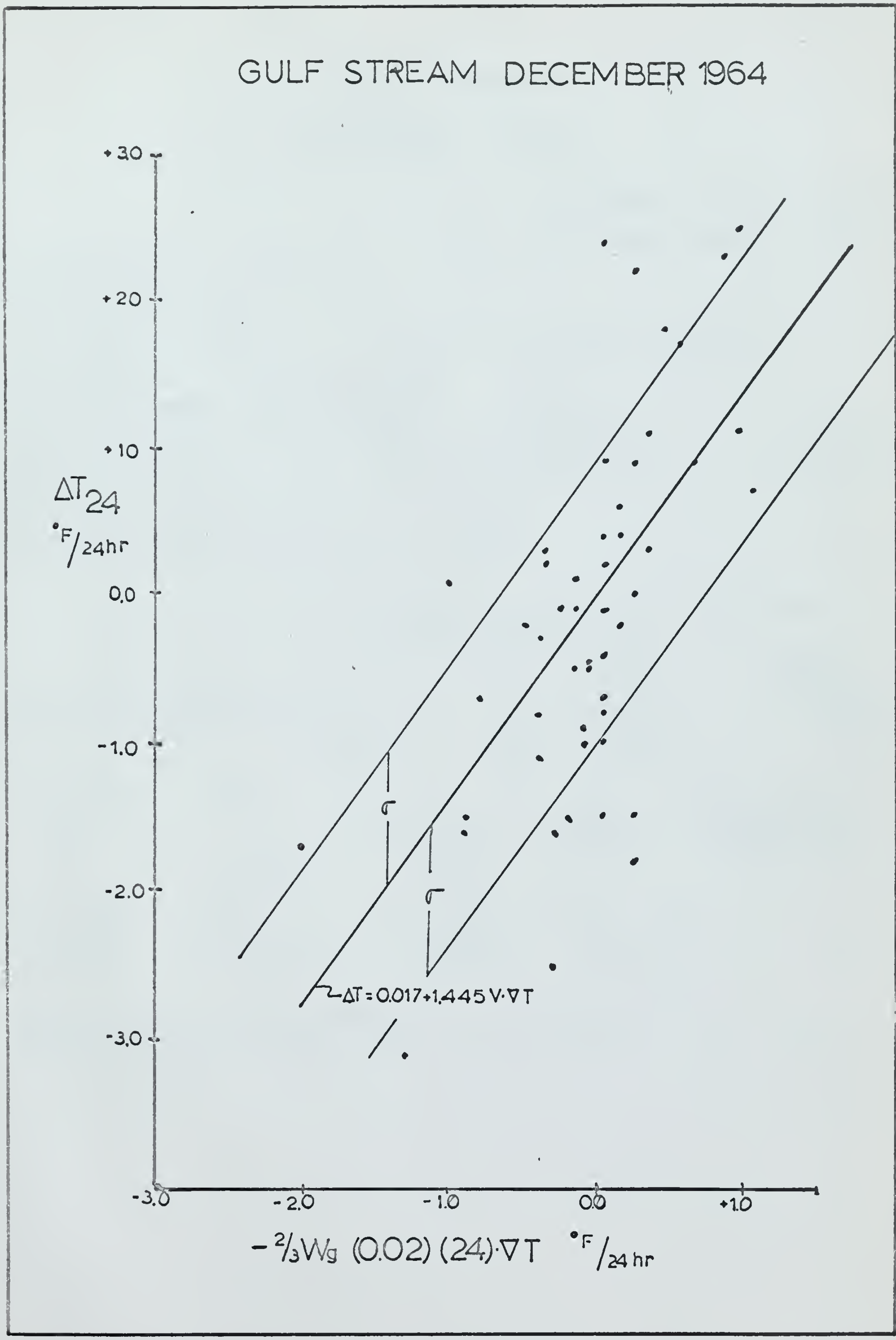
ANALYSIS OF VARIANCE FOR THE MULTIPLE LINEAR REGRESSION

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARES
DUE TO REGRESSION............	1	30.27327	30.27327
DEVIATION ABOUT REGRESSION...	47	44.95162	.95642
TOTAL...	48	75.22490	

VARIABLE NO.	MEAN	STD. DEVIATION	REG. COEFF.	STD.ERROR OF REG.COE.
1	-.08776	.54948	1.44529	.25689
2	-.11020	1.25187		

COMPUTED T VALUE	PARTIAL CORR. COE.	VARIANCE ADDED	PROP. VAR. CUM.
5.62608	.63438	30.27327	.40244

```
COMP. CHECK ON FINAL COEFF.         1.44529
MEASURE OF EFFICIENCY  (STD. ERROR OF EST. / REG. COEFF.)
      .67666
```



GULF STREAM DECEMBER 1964
+3.0
+2.0
+1.0
0.0
-1.0
-2.0
-3.0
ΔT_{24}
°F/24hr
σ
σ
ΔT = 0.017 + 1.445 V·∇T
-3.0
-2.0
-1.0
0.0
+1.0
$-\frac{2}{3} W_g$ (0.02) (24)·∇T °F/24 hr

OSV "XRAY"
SUMMER 1950

Variable no.1 is $V \cdot \nabla T$
Variable no.2 is ΔT_{24}

```
PROBLEM NO.     2- 0
NO DATA TRANSFORMATION
SAMPLE SIZE    64
NO. OF VARIABLES  2        NO. OF VARIABLES DELETED  0
DEPENDENT VARIABLE IS NOW NO.  2
COEFFICIENT OF DETERMINATION     .1971
MULTIPLE CORR. COEFFICIENT       .4439
SUM OF SQUARES ATTRIBUTABLE TO REGRESSION              6.30414
SUM OF SQUARES OF DEVIATION FROM REGRESSION           25.68695
VARIANCE OF ESTIMATE           .41431
STD. ERROR OF ESTIMATE         .64367
INTERCEPT (A VALUE)            .01097
STD. ERROR OF INTERCEPT        .08047
```

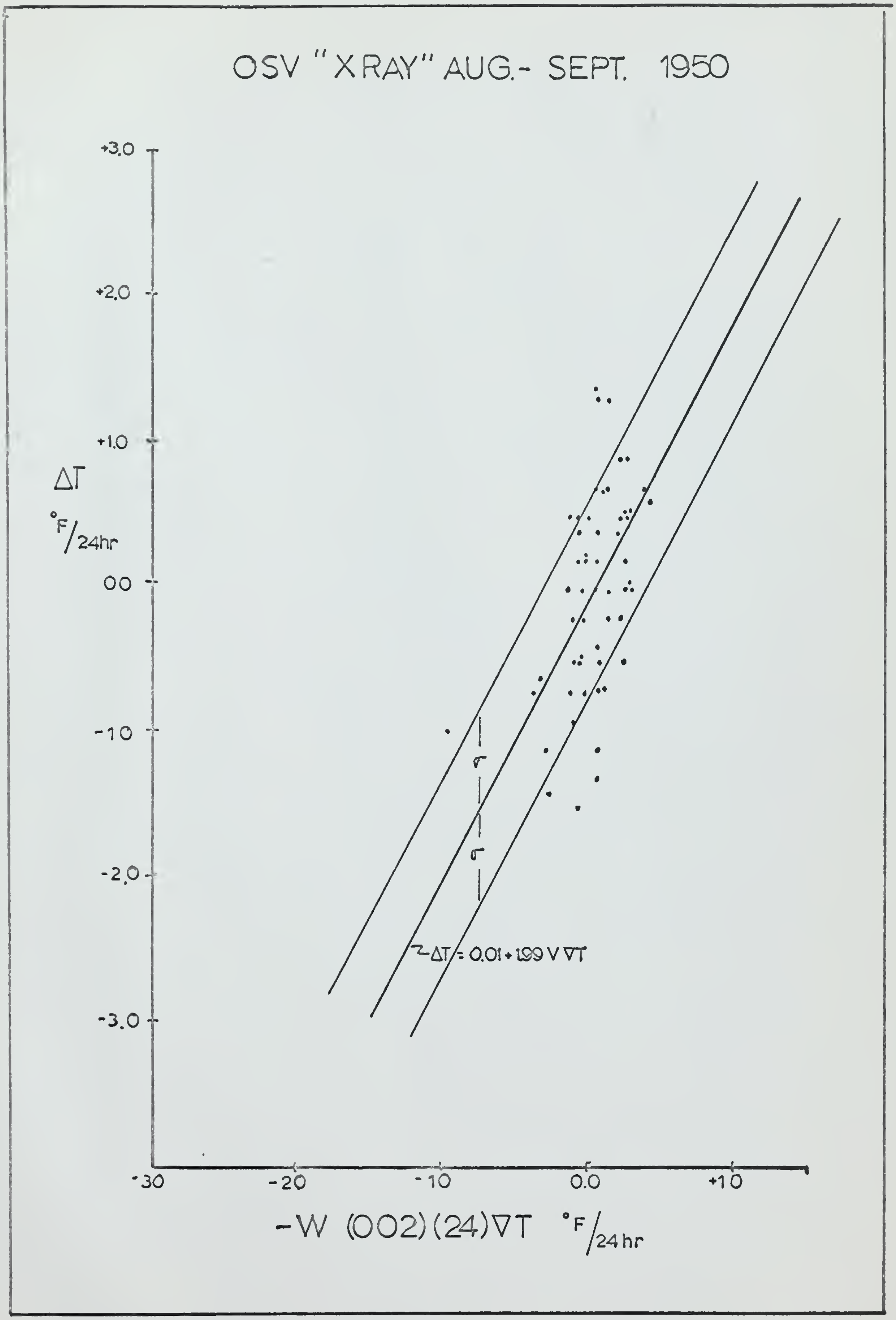
ANALYSIS OF VARIANCE FOR THE MULTIPLE LINEAR REGRESSION

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARES
DUE TO REGRESSION...........	1	6.30414	6.30414
DEVIATION ABOUT REGRESSION...	62	25.68695	.41431
TOTAL...	63	31.99109	

VARIABLE NO.	MEAN	STD. DEVIATION	REG. COEFF.	STD. ERROR OF REG.COE.
1	.00312	.15904	1.98896	.50989
2	.01719	.71260		

COMPUTED T VALUE	PARTIAL CORR. COE.	VARIANCE ADDED	PROP. VAR. CUM.
3.90079	.44391	6.30414	.19706

```
COMP. CHECK ON FINAL COEFF.          1.98896
MEASURE OF EFFICIENCY (STD. ERROR OF EST. / REG. COEFF.)
      .32362
```


OSV "XRAY" AUG.- SEPT. 1950
+3.0
+2.0
+1.0
ΔT
°F/24hr
0.0
-1.0
-2.0
-3.0
σ
σ
ΔT = 0.01 + 1.99 V∇T
-30
-20
-10
0.0
+10
-W (002)(24)∇T °F/24hr